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14. ABSTRACT
In this paper, we discuss the validation of water level and current predictions from three coastal hydrodynamic models and document the resource and operational requirements for each modeling system. The ADvanced CIRCulation Model (ADCIRC), the Navy Coastal Ocean Model (NCOM), and Delft3D have been configured and validated for the Chesapeake Bay region during a Navy exercise. Water level predictions are compared with a NOAA/NOS water level gauge at the Chesapeake Bay Bridge Tunnel location while current predictions are validated with Acoustic Doppler Profiler (ADP) measurement records at three locations in the lower Chesapeake Bay. Statistical metrics such as correlation coefficient and root mean square error (RMSE) are computed. Both the vertically-integrated currents and currents at varying water depths are compared as well. The model-data comparisons for surface elevation indicate all three models agreed well with water level gauge data. The two-dimensional version of ADCIRC, ADCIRC2D, and NCOM yield better statistics, in terms of correlation and RMSE, than Delft3D. For vertically-integrated currents, ADCIRC2D has the smallest RMSE at Thimble Shoal and Naval Station locations while NCOM has the smallest RMSE at Cape Henry. For the horizontal currents over the water column, the fully three-dimensional, baroclinic ADCIRC model, ADCIRC3D, and NCOM both showed better agreement with the ADP measurements.

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Chesapeake Bay, model validation, coastal models, currents, water levels, NCOM, Delft3D, ADCIRC

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Multi-Model Validation in the Chesapeake Bay Region in June 2010 (Draft)

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ABSTRACT

In this paper, we 1) describe the modeling effort by Naval Research Laboratory (NRL) scientists to support a Navy exercise in June 2010, 2) discuss the validation and performance of water level and current predictions on three coastal hydrodynamic models and 3) document the resource and operational requirements for each modeling system.

Three coastal hydrodynamic models, ADvanced CIRCulation Model (ADCIRC), Navy Coastal Ocean Model (NCOM) and Delft3D have been configured, tested and validated for the Chesapeake Bay region during a Navy exercise. Water level predictions are compared with a NOAA/NOS water level gauge at the Chesapeake Bay Bridge Tunnel location while the current predictions are validated with Acoustic Doppler Profiler (ADP) measurement records at three locations in the lower Chesapeake Bay: Cape Henry, Thimble Shoal and Naval Station. Statistical metrics such as correlation coefficient and root mean square error are computed. Both the vertically integrated currents and currents at various vertical water depths are compared as well. The validation results for surface elevation indicates all three models agreed well with water level gauge data. ADCIRC2D and NCOM yield better statistics, in terms of correlation and root-mean-square-error (RMSE), than Delft3D. For vertical-integrated currents, ADCIRC2D has the smallest RMSE at Thimble Shoal and Naval Station locations and NCOM has the smallest RMSE at Cape Henry. For the horizontal currents in the vertical direction, the ADCIRC3D and NCOM showed better agreement with the NOAA ADP measurements. However, all models tend to have a less satisfactory correlation coefficient at the validation locations. Reasons for the errors and low correlation coefficient in current magnitude are possibly due to 1) inadequate spatial and temporal resolution of the COAMPS wind forcing, 2) water depth mismatches among models and measurement location, and 3) insufficient number of vertical layers in Delft3D.

1. Introduction

There is a strong need for the US Navy to develop relocatable, operational coastal forecast systems to support naval missions in coastal and semi-enclosed seas. A Navy exercise in the lower Chesapeake Bay region during June 2010 provided an excellent opportunity to validate the accuracy and performance of three coastal models.

In this paper, we try to describe 1) the modeling effort by Naval Research Laboratory (NRL) scientists to support the exercise; 2) the validation and performance of water levels and currents for three coastal hydrodynamic models: the Advanced Circulation Model for Oceanic, Coastal, and Estuarine Waters (ADCIRC), the Navy Coastal Ocean Model (NCOM) and Delft3D; and 3) the resource requirements including hardware, personnel, training and operations for each modeling system. This paper is organized as follows: Section Two describes model configuration and products. Observational and field data are summarized in Section Three. Model validation and skill assessment are detailed in Section Four. System transition issues and requirements are discussed in Section Five. Conclusions are summarized in Section Six.

2. Model Configuration and Products

1.1 *ADCIRC2D*

ADCIRC is a finite element-based community coastal circulation model that solves water surface elevation using the continuity equation in the Generalized Wave-Continuity Equation (GWCE) form and solves velocity using the momentum equations. Its unstructured grid and unique wetting/drying feature allows accurate modeling of complex coastlines and estuaries at fine spatial scale. This model can be run either as two-dimensional (2D) depth integrated mode or a full three-dimensional mode. The detailed formulation and implementation of this model can be found in Luettich and Westerink (2004 and 2005) and a recently published NRL Validation Test Report (Blain et al. 2010). Two versions, ADCIRC2D and ADCIRC3D, are configured in this validation work and their key differences are summarized below:

1) ADCIRC2D uses v45.11, 2D depth-integrated version, ADCIRC3D uses the full three dimensional baroclinic version 49,
2) ADCIRC2D only computes vertical integrated velocity while the present ADCIRC3D mesh contains 41 sigma layers in the vertical direction,
3) ADCIRC2D has the spatial resolution ranging from 15m to 2km, ADCIRC3D has a coarser spatial resolution with a minimum element spacing approximately 150 m,
4) ADCIRC2D uses a tidal database to provide boundary condition, ADCIRC3D boundary and initial condition is supplied from the U.S. East Coast NCOM forecasts
5) ADCIRC3D uses the Navy Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) (Hodur, 1997) 27-km wind for surface meteorological forcing.

The ADCIRC2D Chesapeake Bay system was configured as follows: the model domain covers

the Chesapeake Bay, Delaware Bay and extends east to the Atlantic Ocean (73W-77W, 36N-40N). The mesh contained 318,860 nodes and 558,718 elements with 15-m spatial resolution in the lower Chesapeake Bay and shipping channels and approximately 2 km at the outer boundary. The grid bathymetry was derived from a combination of NOAA/NOS soundings, the NOAA Electronic Navigation Charts (ENCs) and NOAA Raster Nautical Charts (RNCs). The tidal potential and tidal constituents were extracted from a tidal database derived from the Western North Atlantic Ocean Tidal Model (Yang and Myers, 2007), and eight main tidal constituents were included: Q1, O1, K1, N2, M2, K2, S2, and P1. River discharge was determined to be negligible during the validation period, and was therefore not included as boundary forcing. The bathymetry and numerical meshes for the computation domain are depicted, respectively, in Figures 1 and 2. The validation region in the lower Chesapeake Bay is shown in Figure 3.

This system was configured in March 2010. After a brief spinup and hindcast validation with historical records, daily predictions of water level and currents were produced starting in April 2010, and continued to run in real-time for the duration of the exercise period (June 4 – 11, 2010). The model runs had a time step of 1 second and used 64 CPUs; at NRL, it was executed on a Linux cluster using the Sun Grid Engine (SGE) queue system, on which a 72-hr forecast took approximately 1 hr. Identail runs were performed on the DoD Supercomputing Resources Center (DSRC) host “DaVinci” at the Naval Oceanographic Office (NAVOCEANO). The same model configuration also took approximately 1 hr of wall clock time for a 72-hr forecast. The daily products for the system included hourly 2D maps of water levels and currents in the lower Chesapeake Bay (e.g., Figures 4 and 5). In addition, 6-min water level and current magnitude time series at ten locations were generated daily to support the exercise. Examples of these products are shown in Figures 6 and 7.

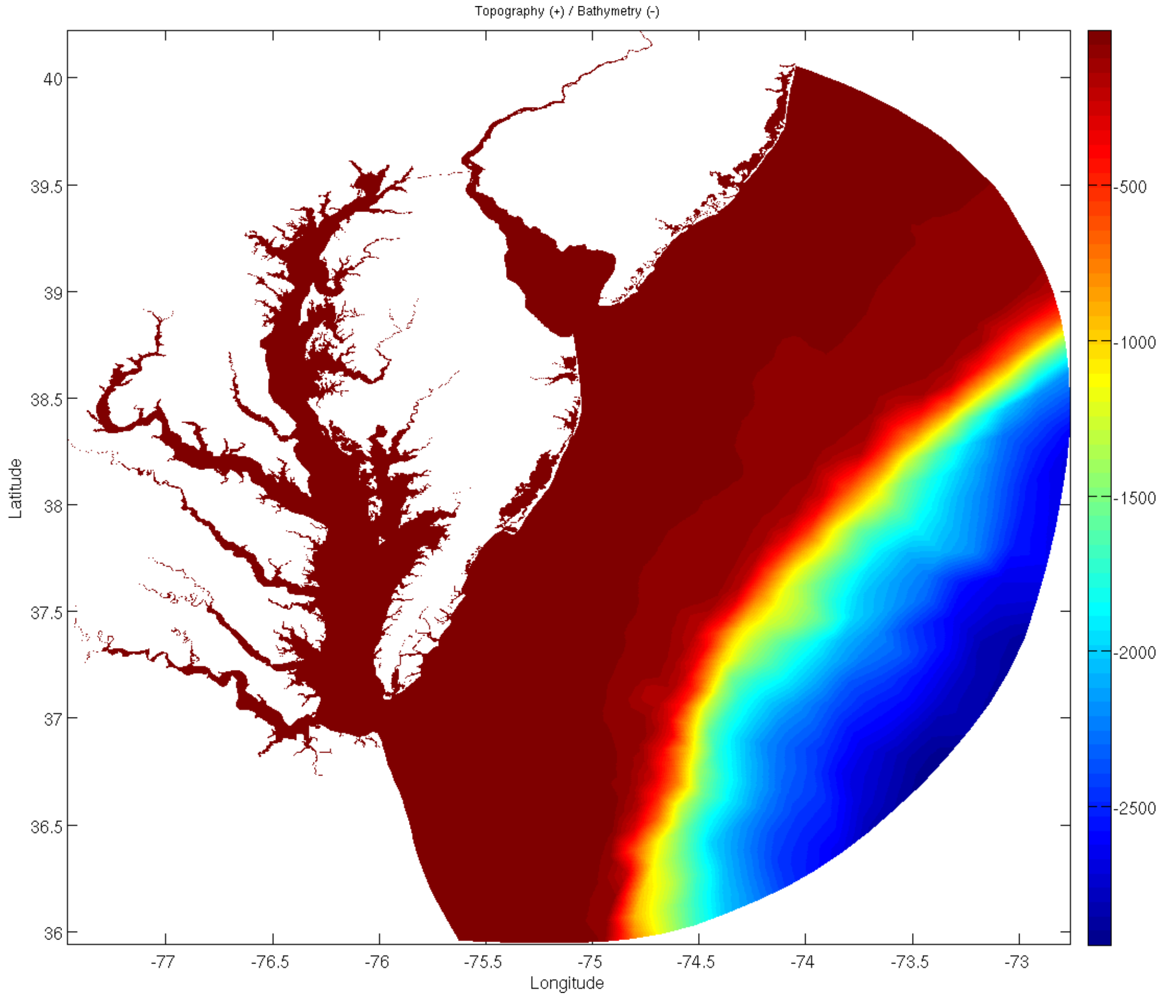

Figure 1. The bathymetry for the ADCIRC domain.

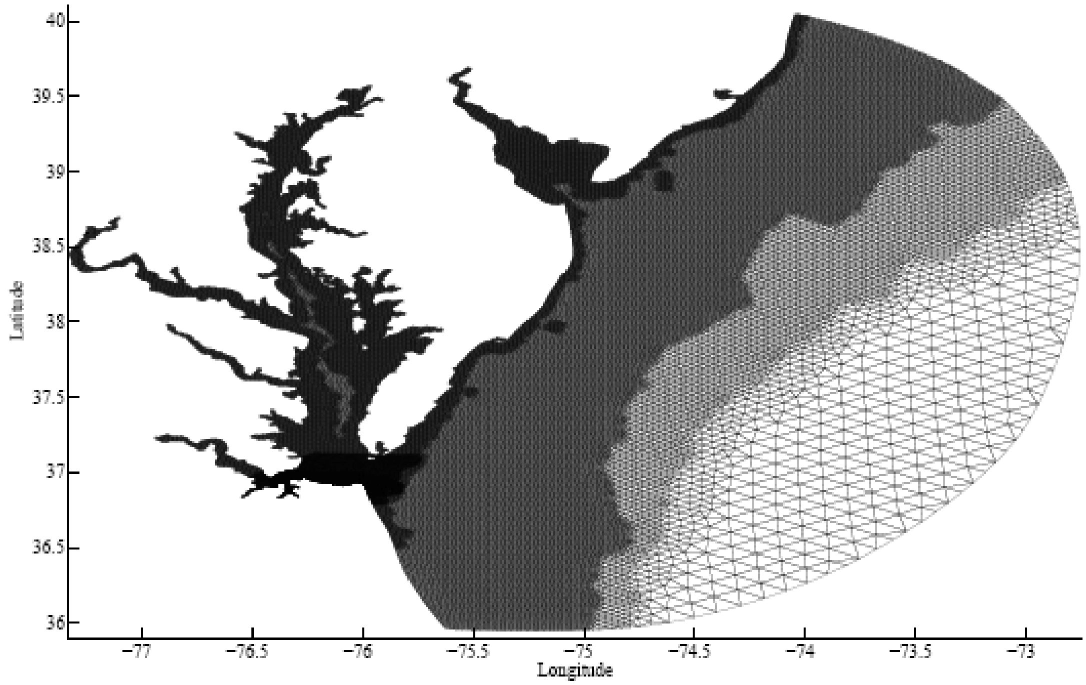

Figure 2. The unstructured mesh used for ADCIRC simulations.

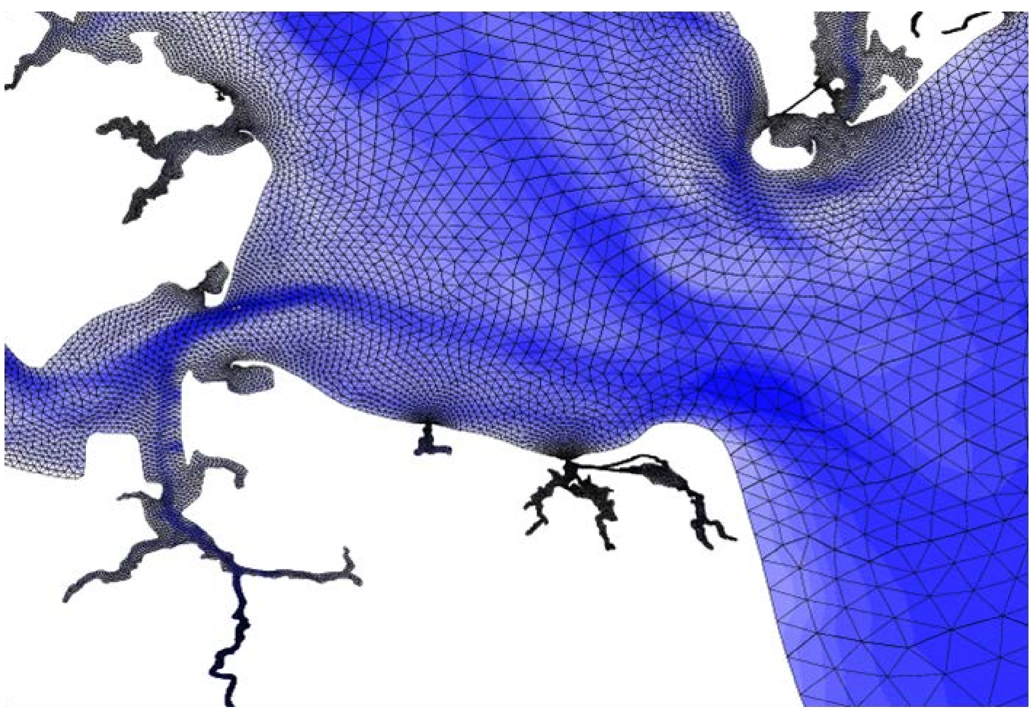

Figure 3. The unstructured mesh of the ADCIRC 2D model in the lower Chesapeake Bay.

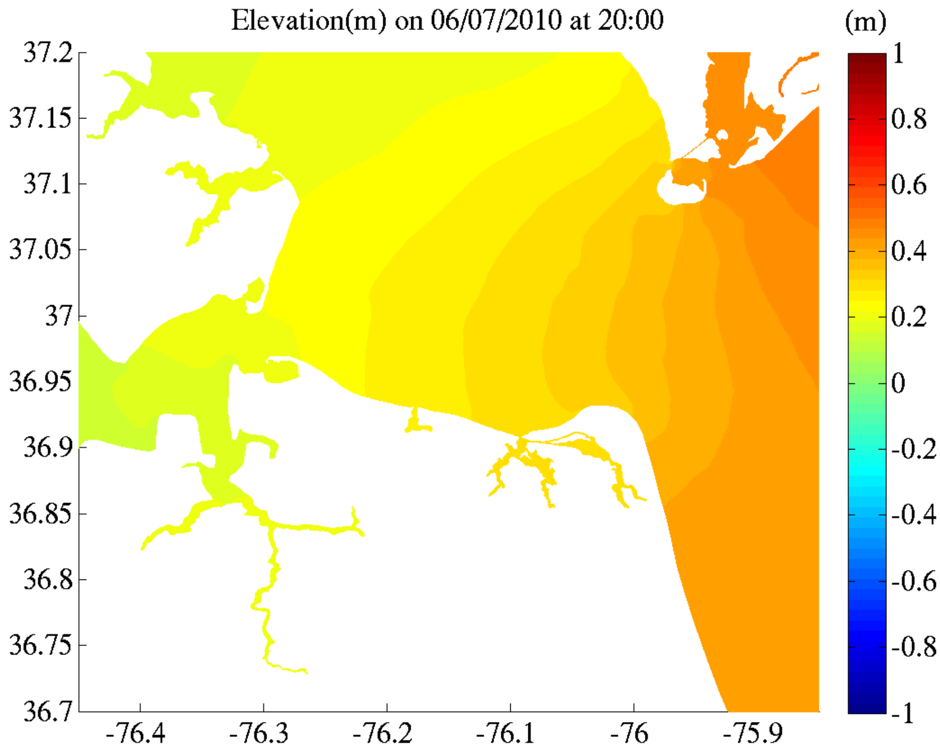

Figure 4. The water surface elevation result from ADCIRC2D on June 7, 2010.

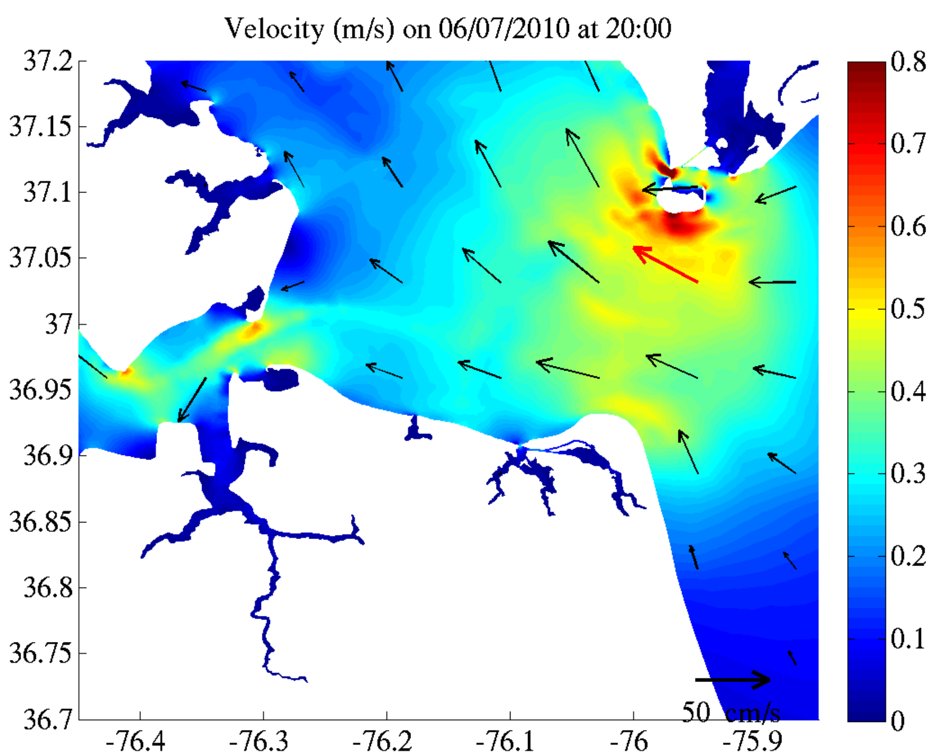

Figure 5. The depth-integrated current result from ADCIRC2D on June 7, 2010. Color is current magnitude

and direction is shown by black arrows.

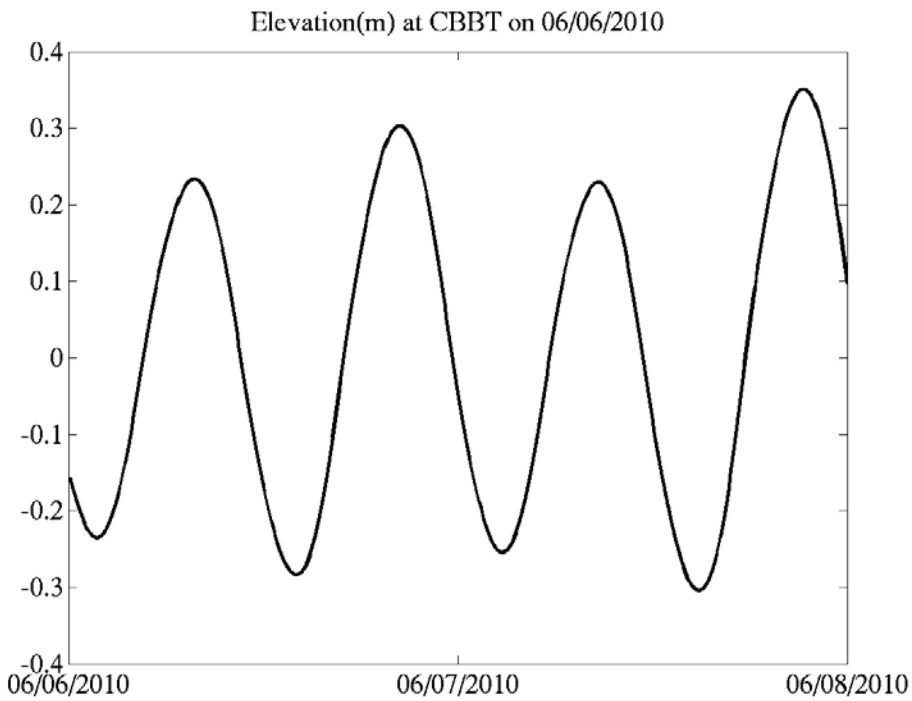

Figure 6. The water surface elevation results from ADCIRC2D from June 6-8, 2010 at the Chesapeake Bay Bridge Tunnel.

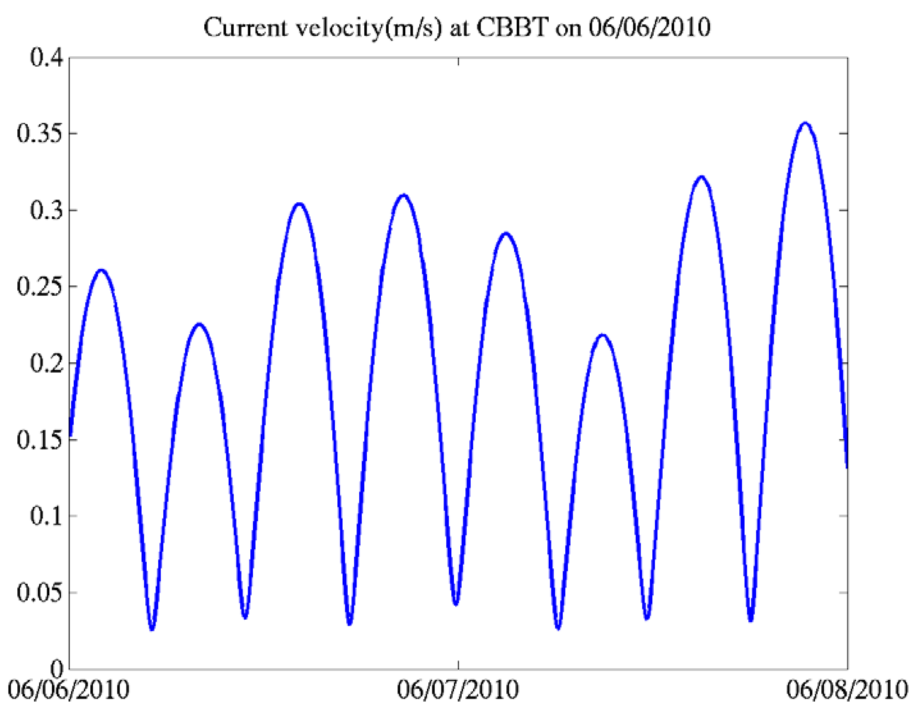

Figure 7. The depth-integrated current result from ADCIRC2D from June 6-8, 2010 at Chesapeake Bay Bridge Tunnel.

1.2 *ADCIRC3D*

As described in previous section, ADCIRC3D use the full three-dimensional (3D) baroclinic version of ADCIRC. This version of ADCIRC solves the transport equations for temperature and salinity using a terrain following sigma vertical coordinate system in which the nodes can be distributed over the vertical direction. The stretched coordinate system is applied to all but the baroclinic pressure gradient term.

The ADCIRC3D domain has the same geographic coverage as the 2D mesh with 99,309 nodes, 192,051 elements and 41 uniformly distributed vertical sigma layers with slightly coarser resolution to about 150 m in the lower Chesapeake Bay. The bathymetry of this mesh was derived from same sources as the 2D version. Boundary and initial conditions were derived from the U.S. East Coast NCOM forecasts. COAMPS 27-km winds at 3-hr intervals was applied for surface meteorological forcing. The surface heat fluxes are calculated using latent and sensible heat fluxes and the shortwave and longwave radiation components provided from COAMPS as well. River discharge was not included as boundary forcing.

ADCIRC3D runs start with a diagnostic run in which the temperature, salinity, and density fields are unchanged. This is intended to spin-up the winds, tides and other barotropic forcing. The diagnostic run is followed by a prognostic run in which full 3D baroclinic calculations are performed and the transport equations for temperature and salinity are solved producing density-driven currents. The Mellor-Yamada 2.5 turbulent closure scheme was selected as the vertical mixing scheme. A suite of tools have been developed to transfer rectangular gridded model fields onto an unstructured ADCIRC mesh, including both the open boundary and interior domain (Dresback et al., 2010). Such tools allow for loose, one-way coupling of ADCIRC3D with NCOM or other models.

The ADCIRC3D system was configured for the Chesapeake Bay region with a time step of 5 s and used 64 CPUs. The SGE parallel computing cluster at NRL was used to make 72-hr diagnostic runs followed by 72-hr prognostic run simulations. Because of the computation requirements and the need to wait for the completion of NCOM forecasts for the boundary conditions, this 3D run was performed in a non-real time delayed mode. The simulations were run daily on 64 CPUs and required approximately 4 hrs of wall-clock time. The performance of the NRL SGE has been comparable to the performance Navy DSRC host DaVinci. Products similar to those produced by the ADCIRC 2D system are also produced by this system.

1.3 *NCOM*

The Navy Coastal Ocean Model (NCOM) is a baroclinic, hydrostatic with Boussinesq

approximation, free surface, data assimilated model developed by the NRL. NCOM uses a Cartesian horizontal grid system, a flexible hybrid sigma-z in the vertical coordinate, an implicit scheme for free surface and Mellor-Yamada level 2 closure for the vertical mixing. Complete descriptions of the model formulation and implementation can be found in Martin (2000) and Barron et al. (2006). NCOM has been transitioned to the NAVOCEANO Operational Production Center to provide daily ocean forecasts to the US Navy at global, regional and coastal scales (Rowley 2008, 2010).

The NCOM model in the Chesapeake Bay region for this exercise is configured in the following fashion: The domain is a 5-by-5 degree area (72.5W-77.5W, 34.5N-39.5N) that covers the Chesapeake Bay and part of the US east coast (Fig 11) at 500-m spatial resolution with 29 vertical layers. The computational domain included more than one million grid points. Bathymetry was derived from the NRL DBDB2 global bathymetry database. Boundary forcing and initial conditions were extracted from the East Coast NCOM which has a 3-km grid resolution. Surface meteorological forcing was applied using the COAMPS forecast meteorological fields.

The NCOM simulations were run daily on 128 CPUs at the Navy DSRC host DaVinci and required approximately 5 hrs of wall-clock time for 72-hr forecasts, including data assimilation and post-processing. In additional to the standard water level and current forecasts, NCOM also generated three dimensional temperature and salinity fields at 3-hr intervals.

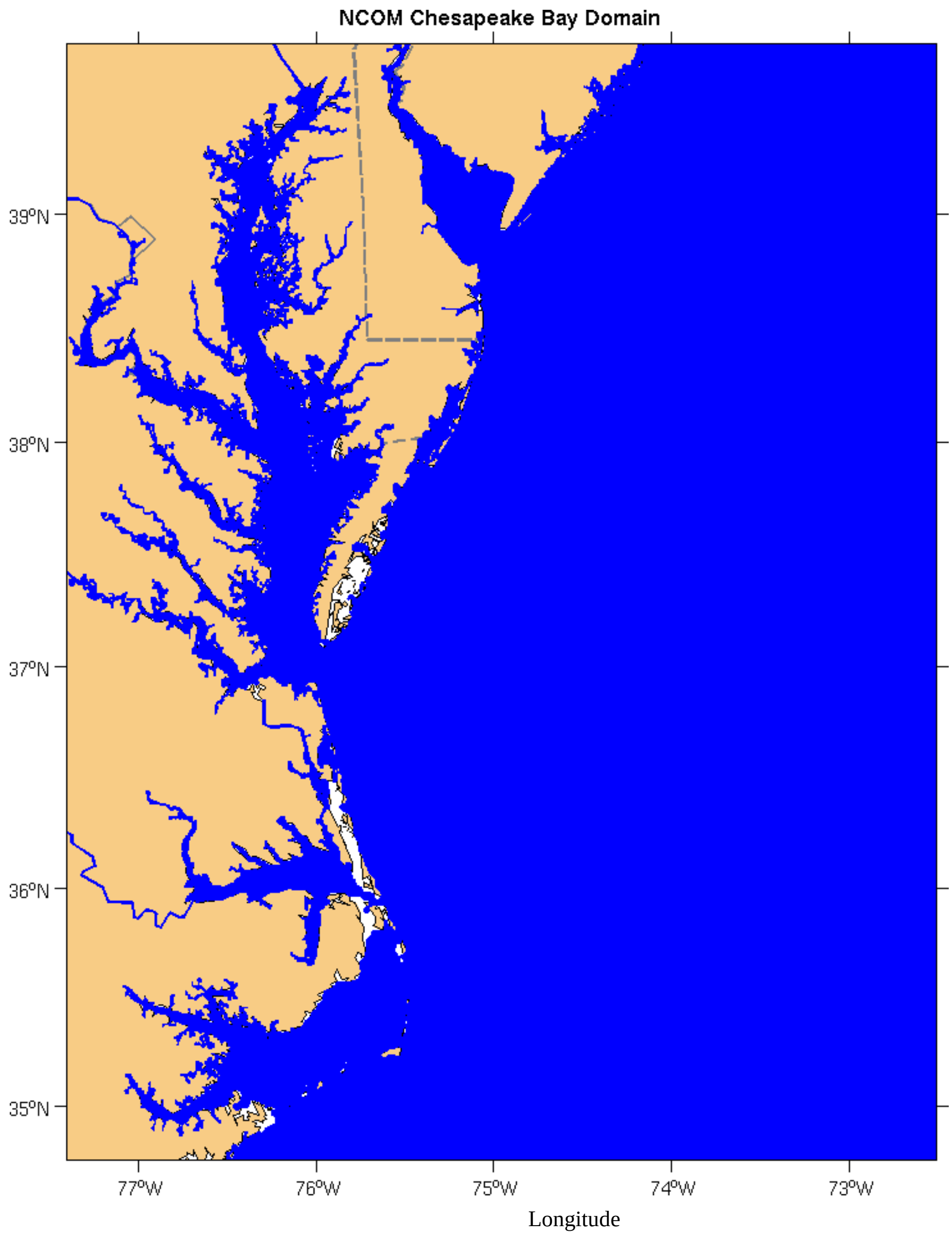

Figure 8. The Chesapeake Bay NCOM domain.

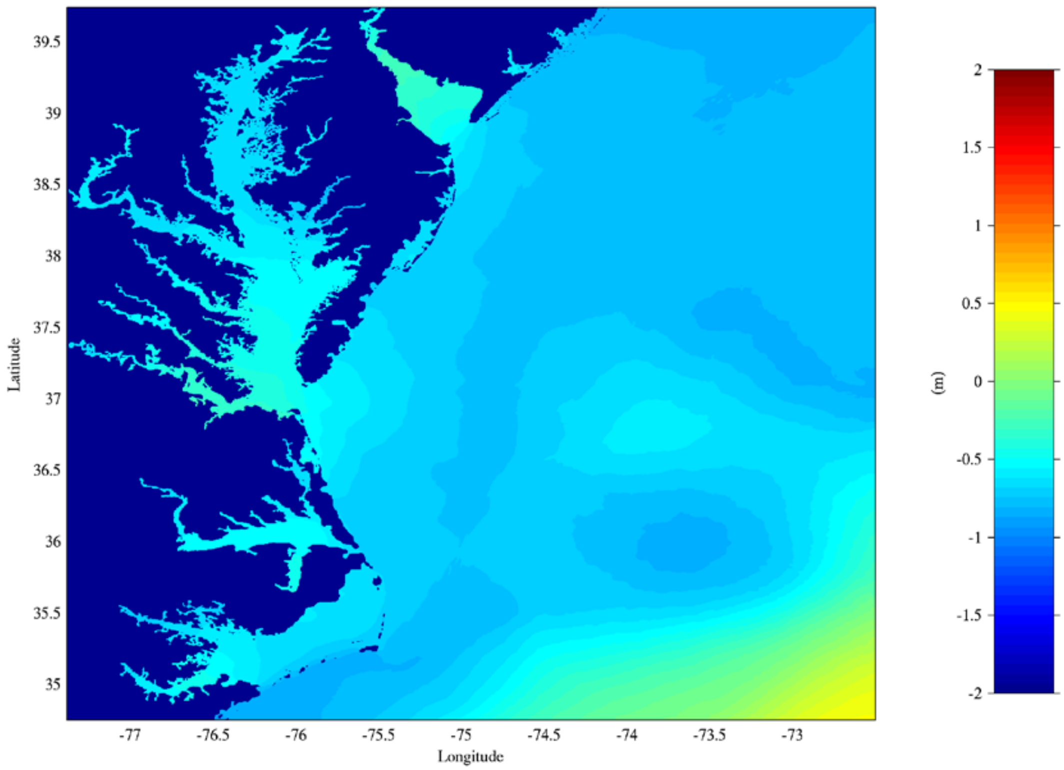

Figure X. The water elevation results from NCOM on 12Z June 7, 2010.

1.4 *Delft3D*

The Delft3D modeling system, developed by Delft Hydraulics (www.deltares.nl), is capable of simulating hydrodynamic processes due to wind, tides, and waves for coastal and estuarine areas. The model can be run in 2D or 3D configuration. A GUI-based preprocessing tool is used to generate curvilinear or rectangular grids in Cartesian coordinates and the post-processing tool allows quick production of graphics and plotting from the native binary model output format (Deltares, 2011). Delft3D can be run on either a personal computer (PC) Windows or Linux platform; however, parallel processing is not currently implemented.

The system was configured with a curvilinear grid with approximately 500 cells in both x and y coordinates at 183-m spatial resolution (Figure 9) and 4 layers in the vertical direction distributed at the surface, 20%, 60% and 100% of the total depth. Boundary conditions also came from the East Coast NCOM model. The 72-hour forecast Delft3D model simulation was executed on a single processor PC. The wall clock time for a single forecast run averaged approximately 5 hr. An example plot showing predicted water level for 0000 hr on June 4, 2010, is shown in Figure

10.

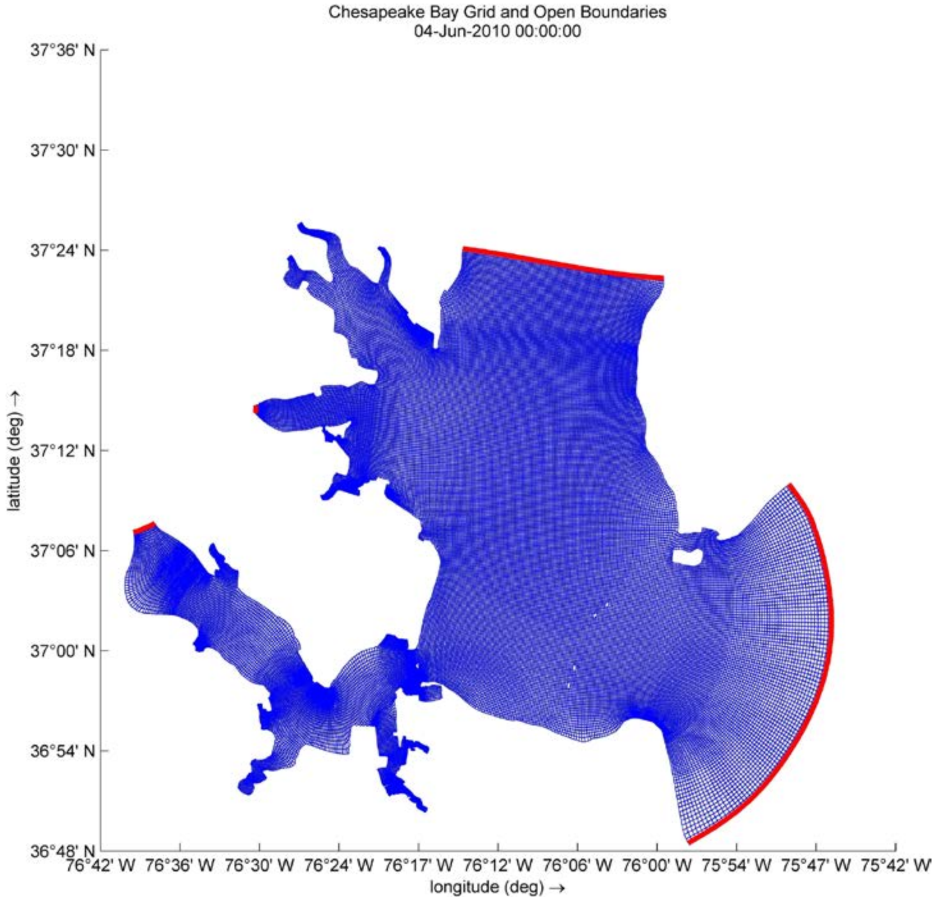

Figure 9. The Chesapeake Bay Delft3D domain.

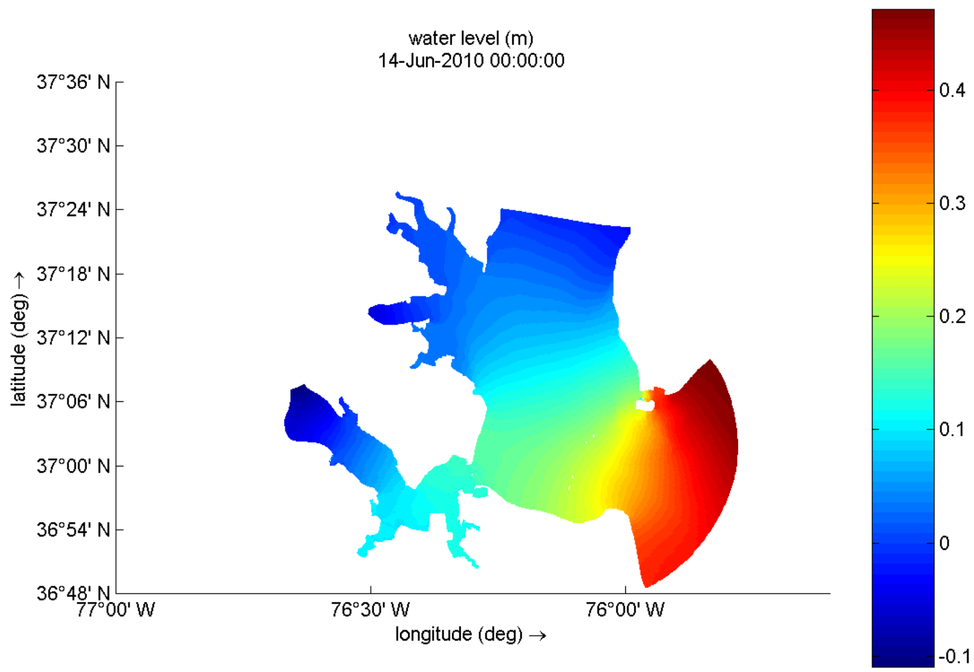

Figure 10. Example of Delft3D water level prediction.

The system configuration for the four models described above is summarized in Table 1.

Table 1. Model Configuration Summary

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
Spatial resolution	15m-2km	150m-12km	500m	183m
Vertical layers	NA	41	29	4
No. of grid nodes	320K unstructured	100K unstructured	1million (1000x1000)	250K (500x500)
OBC forcing	N. Atlantic Tidal Database	EC-NCOM COAMPS	EC-NCOM COAMPS	EC-NCOM COAMPS
Parallel Environment	Yes	Yes	Yes	No

3 Observational Field Data

3.1 *Meteorological conditions*

Several severe storms passed the Chesapeake Bay region during the exercise period, creating challenges for the model-data comparison. Figure 11 shows the wind speed, gusts and directions at the Chesapeake Bay Bridge Tunnel (CBBT) location during the exercise period. There are at least three occasions where wind speed exceeded 12 m/s and a total direction change (360 degrees within just a few hour periods). Preliminary examination of the COAMPS wind fields, which has 27-km resolution at 3-hr time intervals, did not reveal similar magnitude and direction shifts.

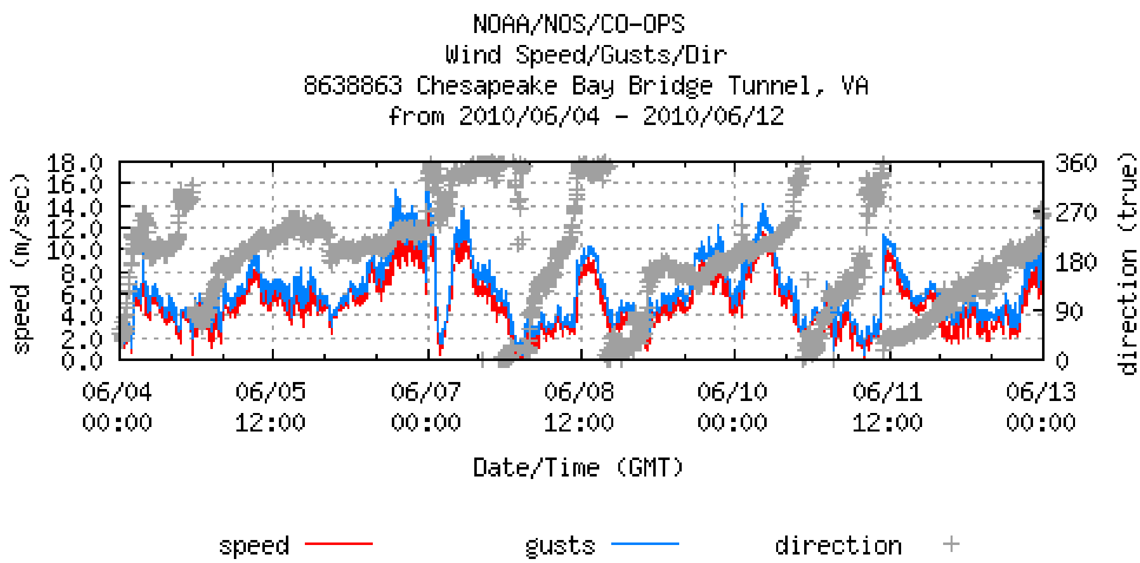

Figure 11. Wind speed, gusts and directions at CBBT location between June 4-12, 2010.

3.2 *Water Level Data*

For the water level analyses, validation data were obtained from NOAA/NOS water level gauge at CBBT. The data at CBBT are recorded in 6-min intervals. Data during the exercise period from the location were used for water level validation.

3.3 *Current ADP data*

Near real-time Acoustic-Doppler Profiler (ADP) records collected by NOAA/NOS at Cape Henry, Thimble Shoal and Naval Station locations (Figure 12) were used to validate the model currents during the exercise period. Three downward-looking ADPs at locations in the bay were used to collect velocity information through the water column. The ADP bin size was 1 m and the sampling rate was 6 min. No detiding procedure has been applied. Since the ADP data used are near real-time, they have not been post processed through the standard NOAA Quality

Assurance/Quality Control (QA/QC) procedure. Industry standard procedures were followed to identify, gap-fill, and interpolate missing records. There were more than 200 missing records during the exercise period. These procedures were required to generate meaningful statistics for the data-model comparison and evaluation.

4 Validation Test Results

4.1 *Introduction*

The data collected by NOAA/NOS during the exercise was used for model validation and comparison. Figure 12 shows the locations of water level gauge at CBBT and NOAA/NOS ADP current meters at Cape Henry, Thimble Shoal and Naval Station.

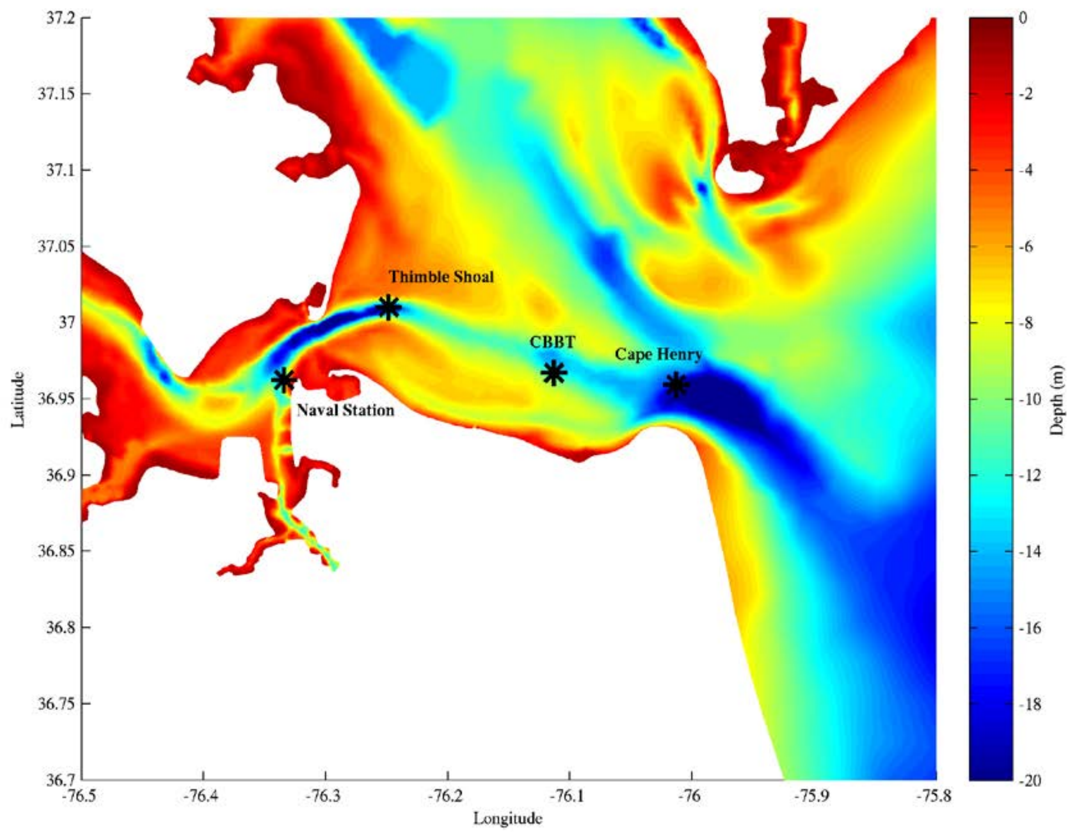

Figure 12. ADCIRC bathymetry with validation locations

4.2 *Water Levels*

For the water level validation, observational data was obtained from the NOAA/NOS water level gauge at the CBBT station. Six-minute interval water level data collected during the exercise period are used for the validation. The model-predicted water level fluctuations are referenced to the Mean Sea Level (MSL) while observational tidal gauges are generally referenced to the NOAA mean lower low water datum (MLLW). Adjustments were made to the model output to match the tidal vertical datum in order to make the statistical comparisons. All three model water level time series results were demeaned and de-trended, then plotted along with tidal gauge data in Figure 13. All three models performed reasonably well for water level prediction. ADCIRC3D tends to over-estimate the water levels while Delft3D results showed a slight phase lag. NCOM shows a phase lead; ADCIRC has good phase characteristics. Table 2 shows the root mean square error (RSME) and correlation coefficient during June 6-14, 2010.

As shown in Table 2, all three models predict the water levels at the Chesapeake Bay Bridge Tunnel measurement station with a high correlation coefficient ($R > 0.75$). ADCIRC2D predictions for the water levels have the least error with the highest correlation coefficient of 0.9. The ADCIRC3D follows with a correlation coefficient of 0.87. NCOM predicts the water levels with a correlation coefficient of almost 0.8 and Delft3D produces water level predictions with the least correlation. The performance of the models in predicting the water levels was also evaluated using the root-mean-square errors. Once again ADCIRC2D performs the best and results in the least error while Delft3D produces the largest error in predicting the water levels.

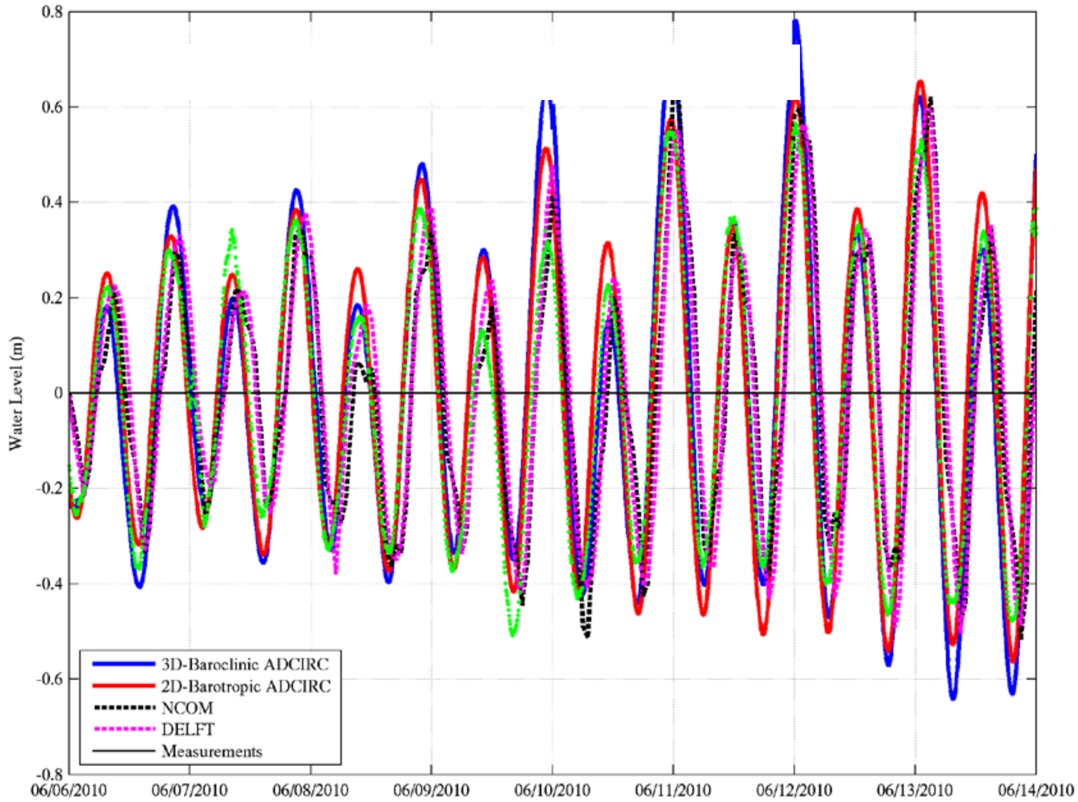

Figure 13. The water surface elevation measured by Chesapeake Bay Bridge Tunnel tide gauge vs. model results between June 6-14, 2010.

Table 2. Summary of water level statistics

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
Correlation Coefficient	0.903	0.865	0.796	0.773
Root Mean Square Error (m)	0.131	0.161	0.171	0.183

4.3 *Vertical-Integrated Currents*

Near real-time NOAA/NOS ADP records at three locations have been used to validate the model currents during the exercise period. Figures 14 to 18 show the measured currents and the model predictions for successive two-day periods at Cape Henry, Thimble Shoal and Naval Station. The ADCIRC2D, directly outputs the depth-integrated currents. For the 3D models, ADCIRC3D,

Regional NCOM and Delft3D, the depth-varying currents through the water column were averaged for comparison. The measured currents are semi-diurnal and the peak currents exceed 1 m/s on only a couple of occasions. It may be seen in the figures that all three models did fairly well in predicting the current magnitude. No single model is observed to stand out with its accuracy and performance according to these qualitative comparisons. In general, all three models seem to underestimate the currents.

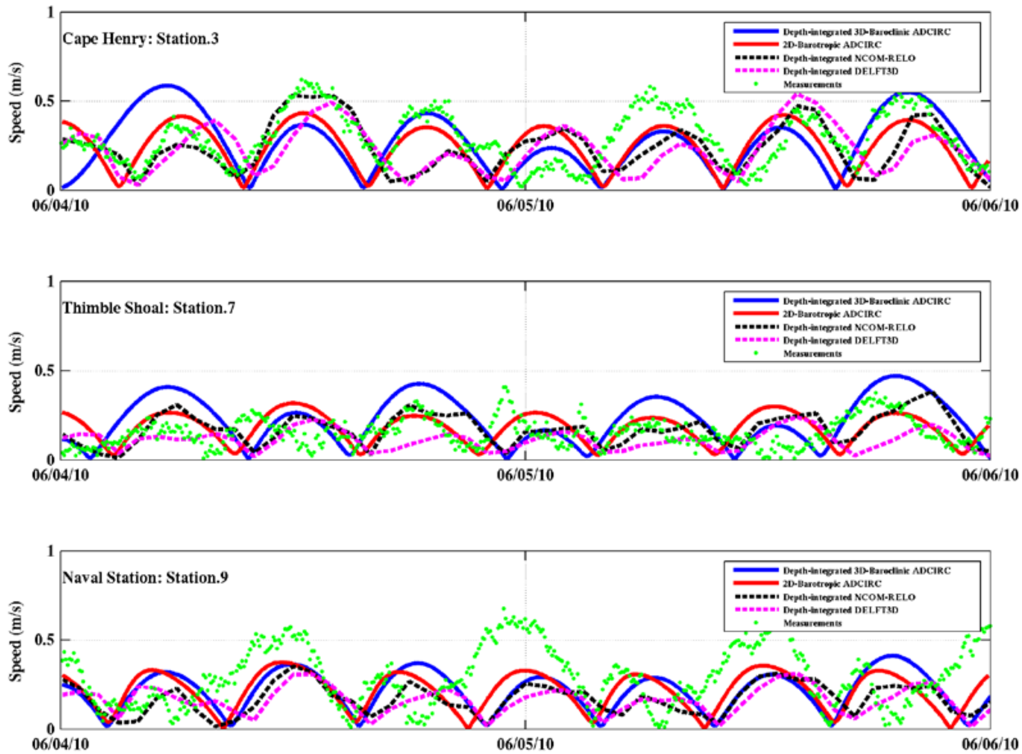

Figure 14. Depth-integrated currents measured at NOAA current meter stations; Cape Henry, Thimble Shoal and Naval Station; compared to the model results from ADCIRC2D, ADCIRC3D, R-NCOM and DELFT3D on June 04-06 2010.

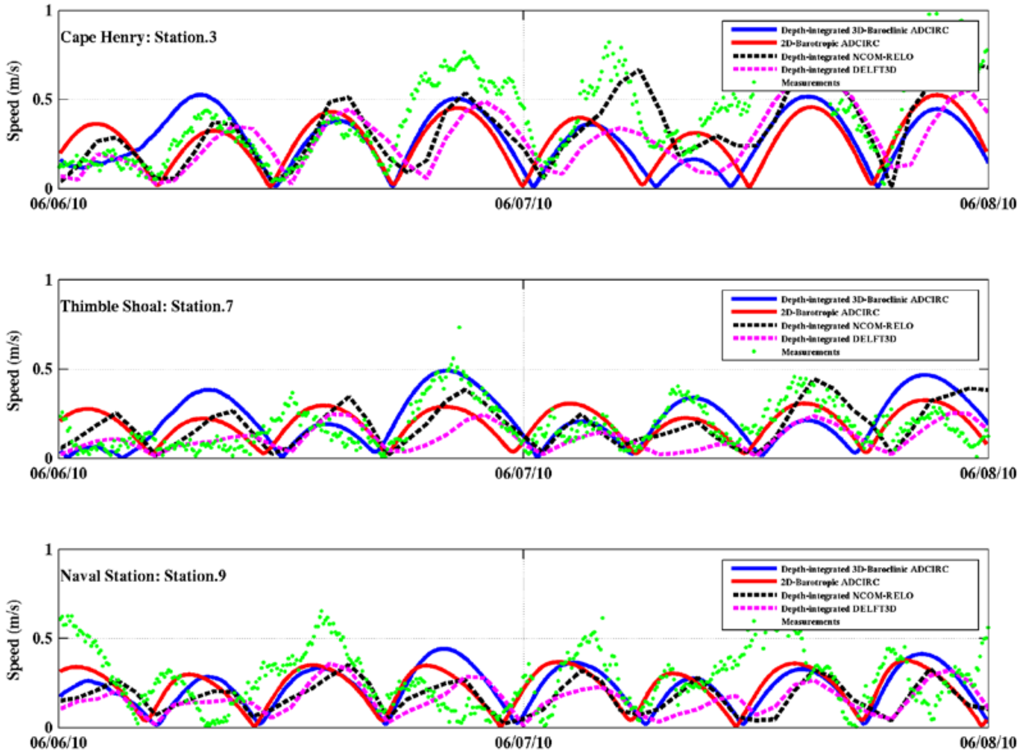

Figure 15. Depth-integrated currents measured at NOAA current meter stations; Cape Henry, Thimble Shoal and Naval Station; compared to the model results from ADCIRC2D, ADCIRC3D, R-NCOM and DELFT3D on June 06-08 2010.

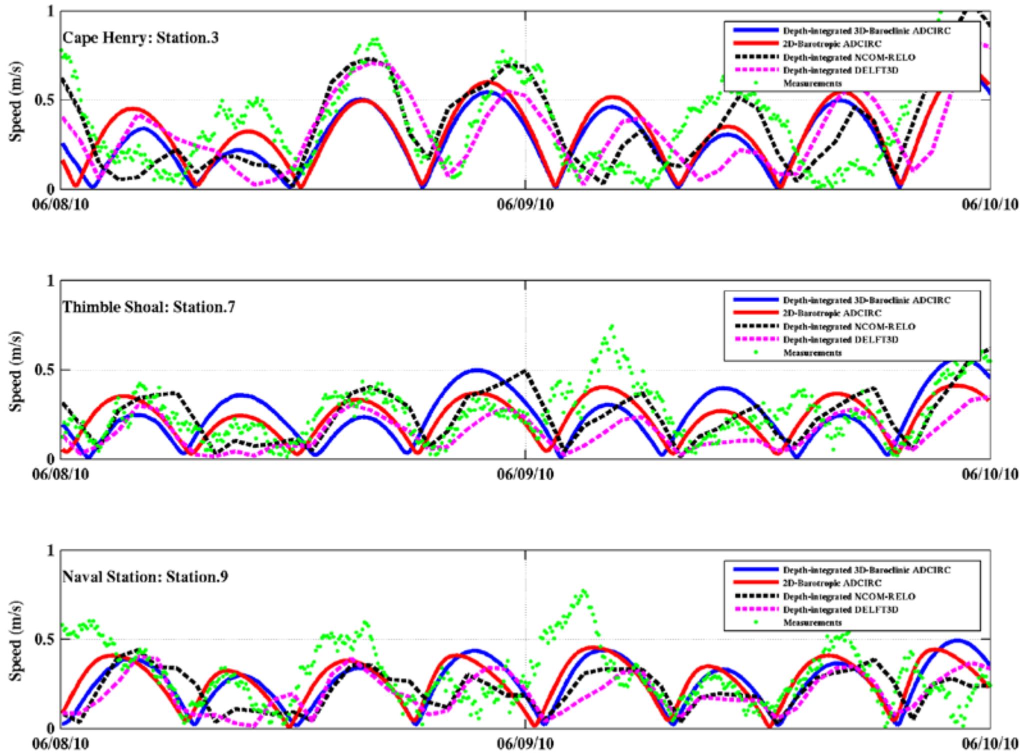

Figure 16. Depth-integrated currents measured at NOAA current meter stations; Cape Henry, Thimble Shoal and Naval Station; compared to the model results from ADCIRC2D, ADCIRC3D, R-NCOM and DELFT3D on June 08-10 2010.

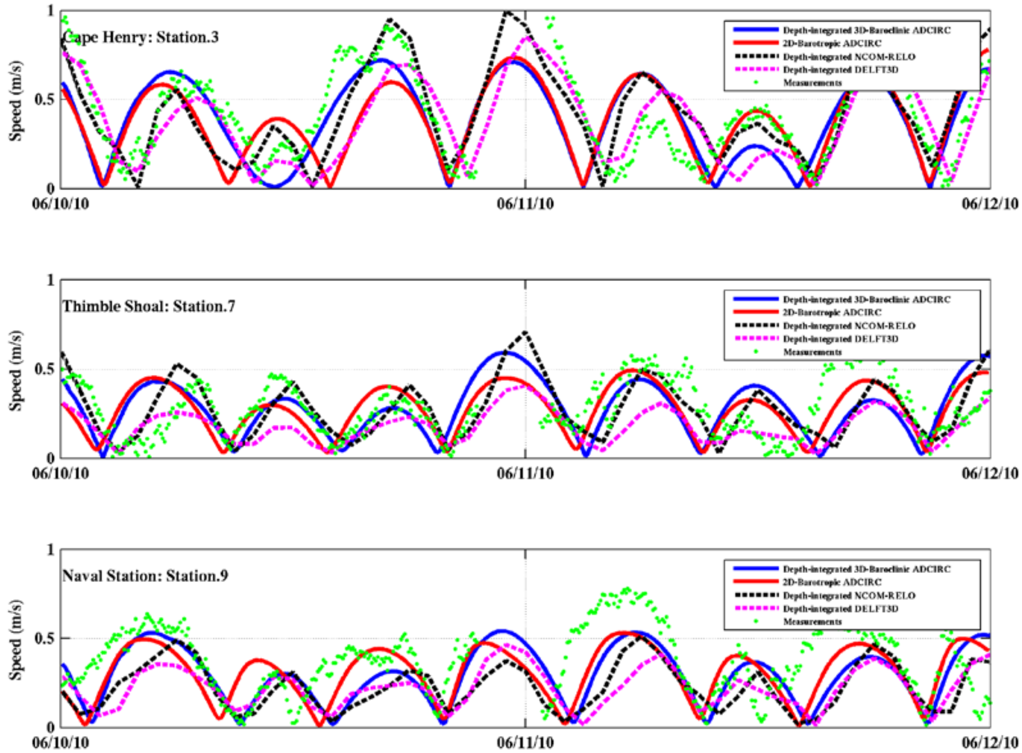

Figure 17. Depth-integrated currents measured at NOAA current meter stations; Cape Henry, Thimble Shoal and Naval Station; compared to the model results from ADCIRC2D, ADCIRC3D, R-NCOM and DELFT3D on June 10-12 2010.

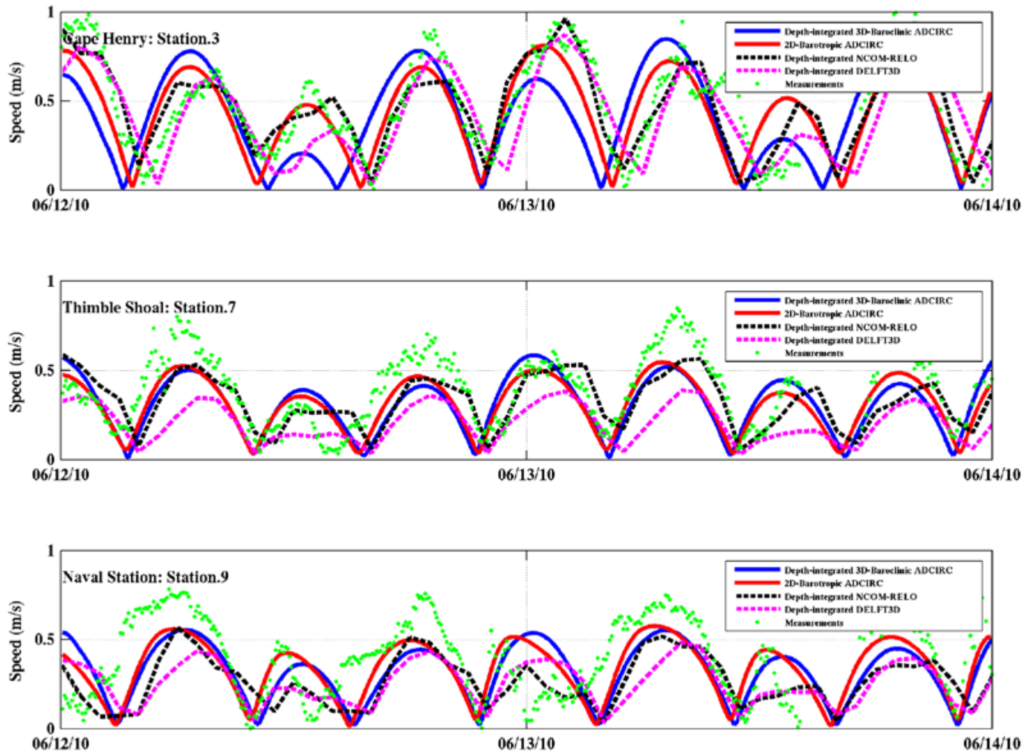

Figure 18. Depth-integrated currents measured at NOAA current meter stations; Cape Henry, Thimble Shoal and Naval Station; compared to the model results from ADCIRC2D, ADCIRC3D, R-NCOM and DELFT3D on June 12-14 2010.

Tables 3-5 show the correlation coefficients of depth-integrated currents for all three models at the Cape Henry, Thimble Shoal and Naval Station locations during June 4-10, 2010. The statistics were calculated for each 48-hr period as well as for the whole 6-day period. NCOM has the highest correlation coefficient (0.745) at Cape Henry while the other models perform similar. On the other hand, ADCIRC2D shows the highest correlation coefficients at Thimble Shoal and Naval Station. A higher correlation coefficient may be considered to indicate less phase error.

Table 3. Correlation Coefficients for Cape Henry Depth-Integrated Currents

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
6/4-6/6	0.513	0.381	0.485	0.220
6/6-6/8	0.494	0.545	0.706	0.539
6/8/6/10	0.375	0.469	0.824	0.466
6/4-6/10	0.439	0.455	0.745	0.463

Table 4. Correlation Coefficient for Thimble Shoal Depth-Integrated Currents

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
6/4-6/6	0.168	0.237	0.024	-0.370
6/6-6/8	0.390	0.429	0.328	0.182
6/8/6/10	0.597	0.223	0.555	0.590
6/4-6/10	0.491	0.299	0.442	0.343

Table 5. Correlation Coefficient for Naval Station Depth-Integrated Currents

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
6/4-6/6	0.365	-0.028	0.184	-0.024
6/6-6/8	0.271	0.021	0.005	0.073
6/8/6/10	0.419	0.084	0.067	0.056
6/4-6/10	0.344	0.027	0.083	0.039

Tables 6-8 show the root-mean-squared errors (RMSE) of depth-integrated currents for all three models at the three stations. Overall, NCOM is observed to have the smallest error over the 6-day period at Cape Henry, and ADCIRC2D has the smallest error over the 6-day period at Thimble Shoal and at Naval Station.

Table 6. RMSE for Cape Henry

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
6/4-6/6	0.145	0.171	0.157	0.189
6/6-6/8	0.264	0.256	0.194	0.254
6/8/6/10	0.285	0.280	0.170	0.277
6/4-6/10	0.239	0.241	0.174	0.243

Table 7. RMSE for Thimble Shoal

	ADCIRC2D	ADCIRC3D	R-NCOM	Delft3D
6/4-6/6	0.108	0.151	0.123	0.129
6/6-6/8	0.117	0.141	0.136	0.141
6/8/6/10	0.123	0.182	0.139	0.165
6/4-6/10	0.116	0.159	0.133	0.146

Table 8. RMSE for Naval Station

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
6/4-6/6	0.177	0.215	0.213	0.227
6/6-6/8	0.174	0.201	0.211	0.211
6/8/6/10	0.152	0.194	0.197	0.206
6/4-6/10	0.168	0.203	0.207	0.215

4.4 *Currents over the Vertical Direction*

The horizontal currents in the vertical direction of all three 3-dimensional models are compared against the NOAA ADP instruments at Cape Henry, Thimble Shoal and Naval Station. Figures 19-23 show the currents at different times during the exercise. NCOM has fixed z-levels and only 7 (at Cape Henry and Naval Station) or 8 (at Thimble Shoal) NCOM levels were available at the measurement locations. Delft3D has 4 vertical levels while ADCIRC3D has 41 levels at all three NOAA/NOS instrument locations.

As ADCIRC3D, NCOM and Delft3D have different vertical resolutions in the vertical direction, and all three models have different bathymetry; correlation coefficients and root-mean-squared errors can be computed only at common depths where all three models and ADP data have current velocities. The model results cannot be compared to the measurements at the surface since the ADP is downward looking and there is a 1.4 m blanking distance while the bottom level cannot be used since Delft3D is deeper than the observations and the other models at Thimble Shoal. As a result, the model-data comparisons are done at the 20% and 60% depth levels of Delft3D. The measurements, NCOM results and ADCIRC3D results have been interpolated to make the comparisons at the same depths.

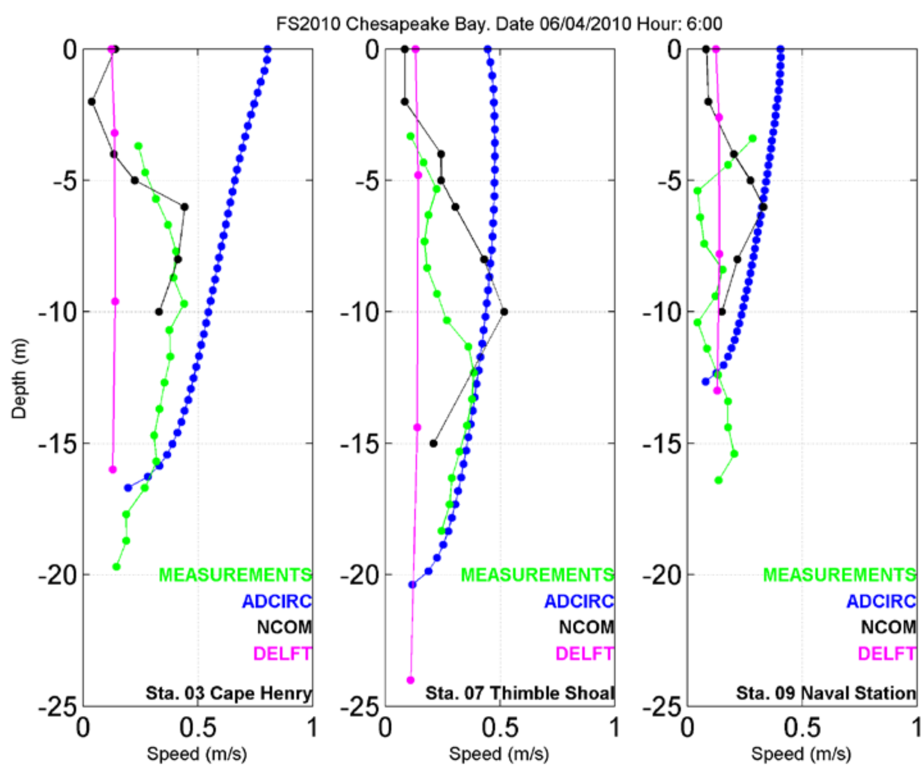

Figure 19. The depth-varying current measurements and model results at Cape Henry, Thimble Shoal and Naval Station NOAA/NOS instrument locations at 0600 hr on June 4, 2010.

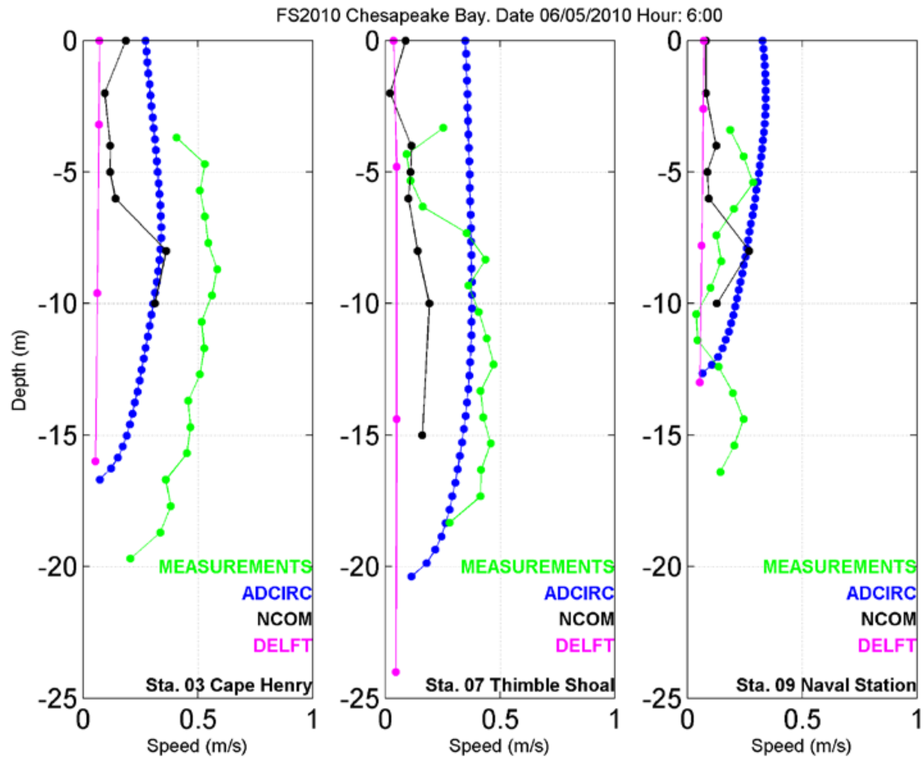

Figure 20. The depth-varying current measurements and model results at Cape Henry, Thimble Shoal and Naval Station NOAA/NOS instrument locations at 0600 hr on June 5, 2010.

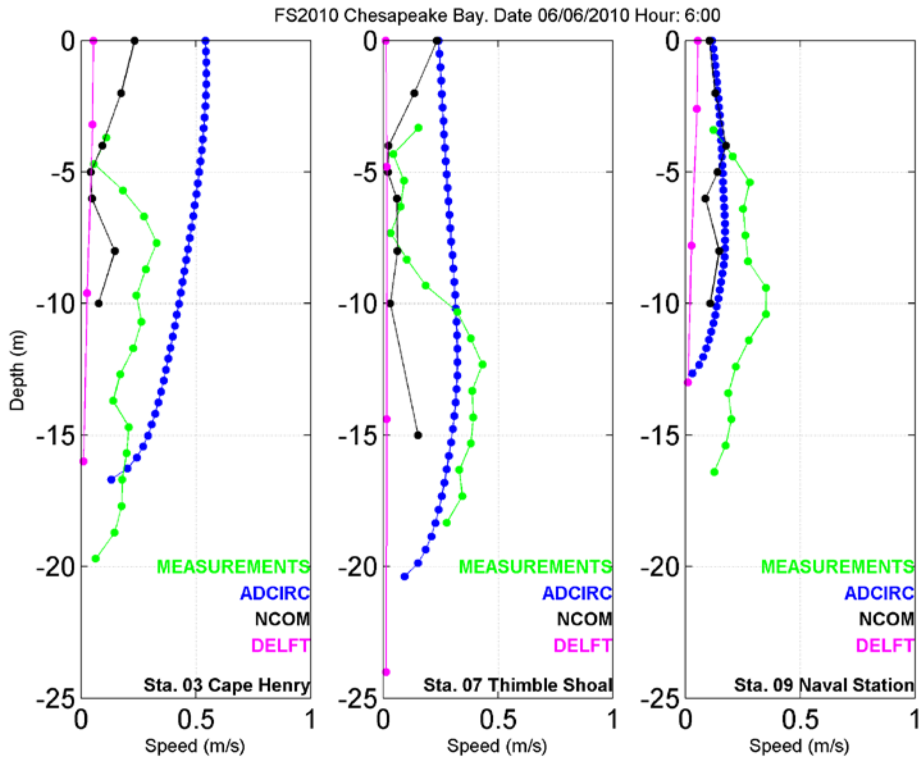

Figure 21. The depth-varying current measurements and model results at Cape Henry, Thimble Shoal and Naval Station NOAA/NOS instrument locations at 0600 hr on June 6, 2010.

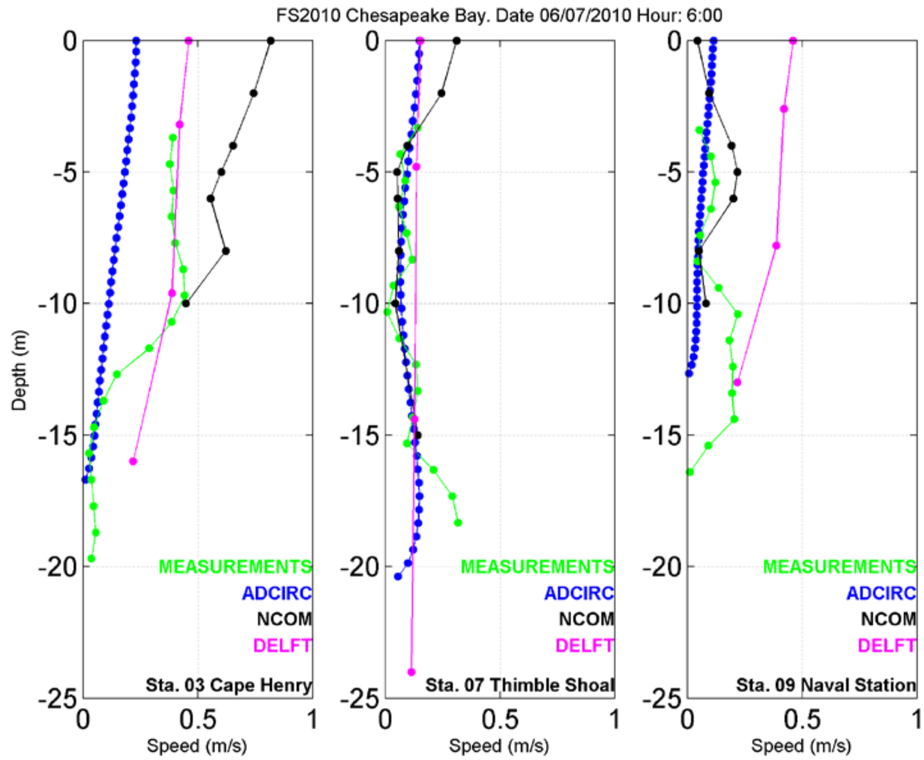

Figure 22. The depth-varying current measurements and model results at Cape Henry, Thimble Shoal and Naval Station NOAA/NOS instrument locations at 0600 hr on June 7, 2010.

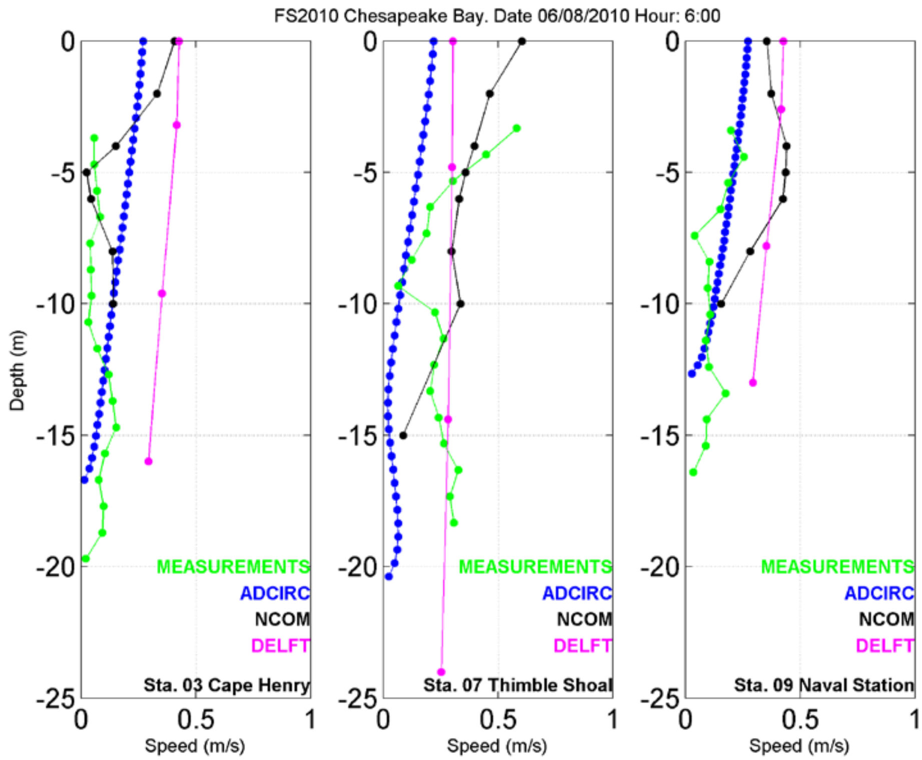

Figure 23. The depth-varying current measurements and model results at Cape Henry, Thimble Shoal and Naval Station NOAA/NOS instrument locations at 0600 hr on June 8, 2010.

Tables 9-11 show the correlation coefficients of model results compared to the ADP measurements at the three locations during June 4-10, 2010. The statistics were calculated at the 20% and 60% Delft3D depth levels, denoted 0.2D and 0.6D, respectively, using hourly measurements and model results. The results show that each model has the highest correlation coefficient at least once at one of the stations during the three 48-hr periods considered. ADCIRC3D and NCOM perform better than Delft3D at Cape Henry and Thimble Shoal. Neither ADCIRC3D nor NCOM is better than the other at Cape Henry. ADCIRC3D has the highest correlation at all times at 0.2D level at Thimble Shoal and NCOM has the highest correlation at all times at the 0.6D level at the same location.

The root-mean square errors were calculated at 0.2D and 0.6D depth levels using hourly measurements and model data, and are presented in Tables 12 through 14. NCOM current predictions have the least error at both vertical levels at Cape Henry except for the 48-hr period of June 6-8, 2010 during which period ADCIRC3D has the least error at 0.6D. At Thimble Shoal, NCOM results have the least error at 0.6D while ADCIRC3D and Delft3D produce current predictions closer to the measurements at 0.2D. Finally, at Naval Station ADCIRC3D results show the least error at 0.2D and NCOM results have the smallest error at 0.6D while Delft3D produces the highest error at both depths. Overall, all three models produce similar error in predicting the currents, but ADCIRC3D and NCOM produce more vertical variability and

hence a more realistic current structure over the water column.

Table 9. Correlation Coefficient of current Profiles at Cape Henry at 0.2D and 0.6D depth

	ADCIRC3D		NCOM		Delft3D	
Depth / Date	0.2D	0.6D	0.2D	0.6D	0.2D	0.6D
6/4-6/6	-0.084	0.500	0.499	0.514	0.187	-0.235
6/6-6/8	0.193	0.606	0.059	0.414	-0.126	0.148
6/8-6/10	0.476	0.381	0.601	0.694	0.373	0.164

Table 10. Correlation Coefficient of current Profiles at Thimble Shoal at 0.2D and 0.6D depth

	ADCIRC3D		NCOM		Delft3D	
Depth / Date	0.2D	0.6D	0.2D	0.6D	0.2D	0.6D
6/4-6/6	-0.120	0.034	-0.125	0.356	-0.289	-0.131
6/6-6/8	0.277	0.215	0.148	0.542	0.100	-0.052
6/8-6/10	0.354	0.039	0.130	0.099	0.279	-0.186

Table 11. Correlation Coefficient of current Profiles at Naval Station at 0.2D and 0.6D depth

	ADCIRC3D		NCOM		Delft3D	
Depth / Date	0.2D	0.6D	0.2D	0.6D	0.2D	0.6D
6/4-6/6	-0.041	-0.008	-0.173	0.137	-0.016	-0.177
6/6-6/8	-0.110	-0.09	0.088	-0.113	0.165	0.038
6/8-6/10	0.128	0.042	-0.138	-0.188	0.017	0.145

Table 12. Root-mean-square error of current Profiles at Cape Henry at 0.2D and 0.6D depth

	ADCIRC 3D		NCOM		Delft3D	
Depth / Date	0.2D	0.6D	0.2D	0.6D	0.2D	0.6D
6/4-6/6	0.258	0.169	0.187	0.154	0.187	0.250
6/6-6/8	0.322	0.256	0.316	0.287	-0.126	0.342
6/8-6/10	0.284	0.256	0.237	0.195	0.373	0.299

Table 13. Root-mean-square error of current Profiles at Thimble Shoal at 0.2D and 0.6D depth

	ADCIRC3D		NCOM		Delft3D	
Depth / Date	0.2D	0.6D	0.2D	0.6D	0.2D	0.6D
6/4-6/6	0.184	0.254	0.142	0.164	0.140	0.201
6/6-6/8	0.158	0.228	0.170	0.182	0.155	0.227
6/8-6/10	0.175	0.274	0.199	0.233	0.216	0.260

Table 14. Root-mean-square error of current Profiles at Naval Station at 0.2D and 0.6D depth

	ADCIRC3D		Regional NCOM		Delft3D	
Date \ Depth	0.2D	0.6D	0.2D	0.6D	0.2D	0.6D
6/4-6/6	0.147	0.185	0.188	0.181	0.221	0.219
6/6-6/8	0.141	0.208	0.144	0.198	0.246	0.238
6/8-6/10	0.176	0.203	0.223	0.220	0.289	0.241

5 System Requirements and Operational Related Issues

5.1 *Hardware requirements*

ADCIRC2D: The system was designed to be independent of the hardware platform. The Chesapeake Bay System was run on the NRL Linux cluster as well as on the NAVO DSRC IBM-P6 DaVinci platform. Both systems were running in real-time during the exercise period. The Linux version used 64 processors and took about 1 hour wall clock time to run 72-hour forecasts. The DSRC version required approximately the same time with the same configuration.

ADCIRC3D: This system was also designed to be independent of the hardware platform. In order to wait for the completion of NCOM output for the initial and boundary conditions, ADCIRC3D was run in delayed mode on the NRL SGE platform during the exercise period. 72-hour simulations with 64 CPUs took 4 hour of wall clock time. Similar computation time could be expected for the DSRC platform since the SGE and the DSRC Davinci are comparable with regard to computation speed for those models.

NCOM: During the exercise, NCOM used the most computational resources: 5 hour wall clock time using 128 CPUs as well as the raw output file size (22GB/day). This is due to the following reasons in the configuration stage: 1) large initial domain containing more than one million grids, 2) relative high spatial resolution at 500 m and small time step during integration, 3) large numbers of vertical layers and 4) the NCODA data assimilation procedure added an additional hour of CPU time.

Delft3D was configured to run on a single CPU PC, with a configuration consisting of 250,000 cells with 4 vertical layers. A 72-hour run took 4-5 hour of wall clock time, and the output files required about 2GB of disk space.

In additional to the computational requirements, one other factor should be considered for an operational daily forecasts is the size of the model output. For example, a typical Regional-NCOM output in compressed format takes more than 22GB of disk space. Archiving and

purging procedures need to be carefully evaluated to prevent disk storage issues. This is especially true for local workstations with limited storage capacity.

Computational resource required to run a typical 72-hour forecast for the Chesapeake Bay region for four models based on the present configuration are summarized in Table 15. Using Delft3D as a benchmark, the ratio of CPU per cell per day for each model was estimated at the end of Table 15.

Table 15. Summary of model computation resource requirements

	ADCIRC2D	ADCIRC3D	Regional NCOM	Delft3D
72-hr run on Davinci	1 hour wall clock on 64 CPUs	NA	5 hour wall clock on 128 CPUs	NA
72-hr run On NRL Linux cluster	1 hour wall clock on 64 CPUs	4 hour wall clock on 64 CPUs	NA	NA
72-hr run on PC	NA	NA	NA	5 hour single processor CPU
Output file size	1GB	5GB	22GB	2GB
CPU in second /cell/day run	0.3	3.0	1.5	0.05
Ratio	6	60	30	1

5.2 *Personnel Requirements*

Personnel resource requirements for running a new geographic region on a regular basis are evaluated based on three categories: 1) initial training, 2) setting up and configuring a new area and 3) daily monitoring and maintenance. Those requirements for each modeling system are summarized in the following table.

Table 16. Model Resource Requirements

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
Mesh/Grid generation	1 hour with MeshGUI	1 hour with MeshGUI	2- 3 hours	Pre-processing grid GUI
System config. /testing	1 week	1week	1 week	1 week
Operational runs	Automatic Shell scripting	Automatic Shell scripting	Automatic Shell scripting	Perl based scripting
Initial training	1 personnel for 2 days	1 personnel for 2 days	2-3 personnel for 2 days	1 personnel for 2 days

Initial Training: All systems have fairly user-friendly software installation scripts and documentation (user's guide and software manual). Two-day training/tutorial sessions should cover all the necessary steps in setting up new geographic domain, using mesh generation tools, modifying run scripts, and operational and maintenance issues.

Setting up a new domain: Both NCOM and Delft3D have a relative simple procedure in setting up a new domain since the rectangular grid can be generated automatically once the user specifies the latitude and longitude of the four corners of the model domain. On the other hand, due to the nature of the triangular unstructured mesh system used by ADCIRC, mesh generation cannot be fully automated at present. One of the concerns regarding the finite element based coastal forecasting system is the time and effort required to setup a new geographic region and generate a mesh. The MeshGUI software was developed to create mesh, and a step-by-step user guide describing how to generate the mesh from scratch was compiled to assist the end users (Blain et al., 2008). Using the NRL in-house developed mesh generation GUI tools, users are able to generate a new domain mesh file for ADCIRC within an hour.

Daily monitoring and maintenance: All four systems employ scripts for automated daily operation once the system is configured. Daily forecasts are fully automated requiring no special maintenance. Minimal monitoring is needed to restart the system in case of interruption in case of 1) missing or delayed input fields, 2) hardware failure and 3) insufficient local storage space.

6 Summary and Conclusions

Three coastal models: one community code-ADCIRC2D/3D, one proprietary model-NCOM and one commercial software-Delft3D have been configured, tested and validated for the lower Chesapeake Bay region during a Navy exercise in June 2010. Water level predictions are compared with a NOAA/NOS water level gauge at the Chesapeake Bay Bridge Tunnel location while the current predictions are validated with ADP measurement records in Cape Henry, Thimble Shoal and Naval Station. Standard statistical metrics such as correlation coefficient and root mean square error are computed. Both vertically averaged currents and currents at various vertical water depths are compared.

The validation results and statistics for surface elevation and vertically integrated currents show ADCIRC2D and NCOM yield better statistics, in terms of correlation and RMSE, than the other two models. For the horizontal currents in the vertical direction, the ADCIRC3D and NCOM showed better agreement with the NOAA ADP measurements.

All three models, ADCIRC3D, NCOM and Delft3D, produced currents that were not always highly correlated with the meteorological observations. This raises the possibility that the

meteorological model forcing was in some way suboptimal. A closer look at the COAMPS, particularly the spatial and temporal resolutions indicated the 27 km resolution at 3 hr interval is not adequate to resolve the fast passing weather system during the exercise period. **[Maybe Kemal could elaborate a bit more on this of reference to Kemal and Cherl Ann's work]**. An improved method of assimilating real-time meteorological station data should be investigated to improve the meteorological forcing input.

Large errors in current magnitude were found at several levels in the vertical direction during model-data comparison. The reasons for those discrepancies and low correlation coefficient values are likely due to 1) water depth mismatches among models and measurement location, 2) inadequate spatial and temporal resolutions for COAMPS wind forcing or, 3) insufficient number of vertical layers for Delft3D.

The resource requirements for each modeling system have also been evaluated. This included benchmark tests on grid generation, model setup and configuration, as well as hardware and operational requirements. ADCIRC2D and NCOM are configured to run automatically in real-time at the Navy DoD Supercomputing Resources Center (DSRC). ADCIRC3D can be configured to run automatically. Delft3D currently runs on a single processor PC or Linux platform, it cannot be configured to run at the DSRC until the parallel version has been implemented.

In summary, water levels and currents predicted by ADCIRC and Regional NCOM models showed better agreement than that of Delft3D when compared with the Chesapeake Bay field data during the exercise. The present 4 vertical layer configuration cannot adequately resolve the dynamics in the water column, and the bathymetry data used in the morphological grid should be verified with NAVO DBDB2 bathymetry database or field survey data. All models would benefit from higher spatial and temporal resolution meteorological forcing.

Acknowledgment

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